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Radiative decays of massive neutrinos

Francois Vannucci

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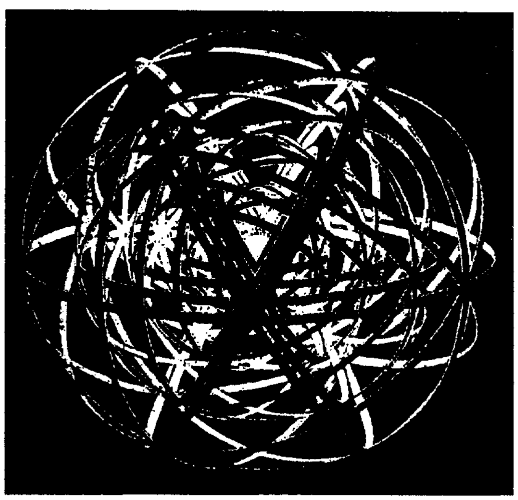

4, Place Jussieu - Tour 33 - Rez-de-Chaussée
75252 Paris Cedex 05

Tél: 33(1) 44 27 63 13 - FAX: 33(1)44 27 46 38

RADIATIVE DECAYS OF MASSIVE NEUTRINOS

F. VANNUCCI
LPNHE Univ. Paris 7, France

ABSTRACT

Radiative decays of massive neutrinos are described. In particular a measurement of solar neutrino decays is presented.

1. Introduction

If neutrinos are massive, they most probably decay. The allowed modes depend on the mass of the decaying parent particle. For large enough masses, various channels open up, for example:

$$\nu_2 \rightarrow e^+e^-\nu_1 \ .$$

This is the dominant mode as soon as $m(\nu_2) > 1.1$ MeV. Several limits have been put on decay channels involving charged particles in the final state.[1] For small masses which are of cosmological relevance (some 1 to 30 eV), the only allowed decay mode is the radiative one:

$$\nu_2 \rightarrow \gamma\nu_1 \ .$$

This process corresponds to the Feynman graph shown in Fig. 1 where the loop runs over charged leptons and the W. The decay mode with two photons has also been considered. It becomes dominant above a mass of 100 keV and does not concern us here.[2]

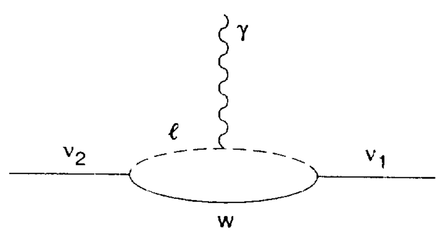

Figure 1: Feynman diagram for the radiative decay.

2. Radiative Decays in the Standard Model

The decay width has been calculated several times in the literature.[3] The graph is GIM suppressed with a sum over the various charged leptons which gives the factor:

$$|\sum_{\ell} U_{1\ell}\, U_{2\ell}\, (m_\ell^2/m_W^2)|^2 \ .$$

The mixing matrix element between the mass eigenstate ν_i and the weak eigenstate ν_ℓ is denoted by $U_{i\ell}$.

With the three known neutrinos there comes the term $(m_\tau/m_W)^4$ and the decay width results in:

$$\Gamma_v = (7 \times 10^{43} s)^{-1}(m_2/1\ eV)^5(1-x^2)^3(1+x^2)|U_{1\tau}U_{2\tau}|^2$$

with $x = m_1/m_2$.

This is a very very long lifetime considering that the age of the Universe is only 10^{17} s.

It is possible to enhance somewhat the decay probability, for example assuming a fourth generation with a heavier charged lepton, but this is not probable after the LEP results, or assuming new contributions of charged Higgses.

In any case, it remains difficult to imagine an enhancement large enough to bring the lifetime to testable ranges.

3. Radiative Decays in a Medium

The situation is quite different in a medium and two possibilities have been contemplated in the literature.

3.1. 'MSW' Effect in Matter

The MSW effect has been studied primarily in the case of oscillations. It is due to the influence of matter which is a medium rich in electrons but which does not contain muons or taus. A similar effect exists in the case of radiative decays.[4] It was first calculated as an effect on the refractive index of the medium but it was then recognized that the process can be calculated in the Standard Model as the coherent interaction of neutrinos on atomic electrons, as shown in Fig. 2. In this case the electron does not change its momentum. The result is impressive. Compared to the decay probability Γ_v in a vacuum, it gives:

$$\Gamma_m/\Gamma_v = 8.6 \times 10^{23} F(N_e/10^{24}\,cm^{-3})^2(1\ eV/m_2)^4\ .$$

This seems a huge enhancement but the factor F tends to $4m_2/E_2$ which is small for any physical neutrinos. The result is still too low to be experimentally relevant in the laboratory.

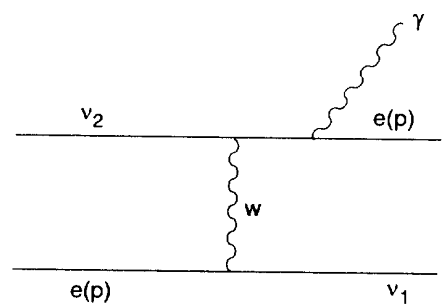

Figure 2: Coherent interaction on atomic electrons.

3.2. Catalysis in a Magnetic Field

A series of papers [5] have considered the effect of an external field on the radiative decay. Again the influence of the field avoids the GIM suppression existing in the vacuum. Also here the enhancement seems huge:

$$\Gamma_{\rm f}/\Gamma_{\rm v} = 10^{33}(1\ {\rm eV}/m_2)^6(E_\nu\omega/m_{\rm e}^2)^5(10^3K_{\rm e}^2)^2$$

with the parameter of the wave intensity $K_{\rm e}^2 = -(e^2a^2)/m_{\rm e}^2$.

This result needs confirmation and even with such a huge benefit, it is not straightforward to devise an experimental test.

4. But ... Are Neutrinos Massive?

All this discussion is relevant only if neutrinos are massive. There are no firm indications yet, but there exist several hints:

(1) The sun abundantly produces $\nu_{\rm e}$'s which are only partially detected on Earth. This deficit which varies with the energy of the neutrinos is interpreted as a sign of matter oscillation in the sun.[6] The solution gives the mass relation:

$$m^2(\nu_{\rm e}) - m^2(\nu') = 10^{-5}\,{\rm eV}^2$$

where ν' is a different neutrino in which the initial $\nu_{\rm e}$ has oscillated.

(2) Several experiments claim a deficit of ν_μ in the atmospheric flux,[7] while $\nu_{\rm e}$'s are seen at the predicted level. This again can be interpreted as an oscillation with the mass relation:

$$m^2(\nu_\mu) - m^2(\nu'') = 10^{-2}\,{\rm eV}^2$$

where ν'' is the neutrino species in which the ν_μ may have oscillated.

(3) The Los Alamos experiment LSND [8] has claimed evidence for the oscillation $\bar{\nu}_\mu$ into $\bar{\nu}_e$. Assuming CP conservation, this gives the mass relation:

$$m^2(\nu_\mu) - m^2(\nu_e) = 6 \text{ eV}^2 \ .$$

(4) The neutrinos will play a role in cosmology and explain part of the missing mass of the Universe (mixed dark matter model) if the masses of the three neutrinos fulfil the relation:

$$\sum m(\nu) \simeq 10 \text{ eV} \ .$$

(5) The theory gives a plausible understanding of the smallness of the neutrino masses. This is the see-saw model which predicts a strong hierarchy between the three masses:

$$m(\nu_e) \ll m(\nu_\mu) \ll m(\nu_\tau) \ .$$

Can we put some order into these various propositions?

Restricting ourselves to the three known neutrinos, it is tempting to identify ν' and ν_μ on the one hand, ν'' and ν_τ on the other hand. But then it is easy to see that the five propositions stated above are not compatible.

Note that (1) and (3) are not contradictory, although they concern the same channel ν_e oscillating into ν_μ. In a three-neutrino phenomenology, the probability of ν_e ν_μ oscillation depends on three terms whose relative importance depends on the experimental conditions. The LSND result can reflect the third neutrino mass which gives an effect at small distance but with a small probability, while the solar deficit corresponds to a larger mixing which develops over longer distances.

Depending on one's own prejudice about the reliability of the experimental results, one can build two possible scenarios for the three masses:

- If one rejects the atmospheric neutrino claim, the four remaining propositions are compatible and one finds the approximate masses:

  $$m(\nu_\tau) \simeq 2.5 \text{ eV}, \quad m(\nu_\mu) \simeq 10^{-3} \text{ eV}, \quad m(\nu_e) \simeq 10^{-7} \text{ eV} \ .$$

  This is a solution close to the one usually preferred and which dictates experiments such as CHORUS and NOMAD.

  But one can also take at face value the atmospheric neutrino result and accept the solar neutrino interpretation. In that case the LSND result has to be discarded. Insisting on a cosmological role for the neutrinos, an acceptable solution consists of three mass-degenerate neutrinos, each of them having a mass of a few eV.

This second solution has not been put to the test as much as the first one, and in particular the limits on radiative decays are rather weak in this case.

5. Existing Limits

Supernova 1987A exploded emitting 10^{58} neutrinos of all species with an energy of about 10 MeV in a few seconds. Neutrino interactions, probably of the ν_e type, were clearly seen on Earth in two experiments.[9]

The explosion took place 150 000 light-years away from us. A radiative decay *en route* to the Earth would have given photons. No excess has been detected in the range 4.1–100 MeV by the Solar Maximum Mission satellite,[10] and a lifetime limit could be extracted:

$$\tau > 6 \times 10^{15} \text{ s } (m/\text{eV}) .$$

Owing to the energy threshold in the detector, this limit applies to the scheme where the decaying neutrino has a mass much larger than the neutrino in the final state, namely our first scenario. More recently this limit has been extended with the data from another satellite.[11]

In the case of mass-degenerate neutrinos, a laboratory limit was also obtained at the Bugey reactor.[12] Visible photons were searched for with a photomultiplier positioned near the high flux reactor. No excess photons were detected and a limit could be achieved for mass-degenerate neutrinos:

$$\tau > 2000 \text{ s} \qquad \text{for } \delta m/m = 10^{-3} ,$$

but this limit only applies to a decaying ν_e.

6. Solar Neutrino Decays

The mass-degenerate scheme allows new ideas to be tested. In particular solar neutrinos offer an intriguing possibility.

The present interpretation of the solar puzzle favours an almost complete disappearance of the 860 keV peak of ν_e from ^{7}Be. They have oscillated into a different neutrino type ν' which is not detected.

If one accepts this hypothesis, a 'beam' of 5×10^9 $\nu'/\text{cm}^2/\text{s}$ arrives on Earth with a well-defined energy of 860 keV and a mass relation with the initial ν_e:

$$\delta m^2 = 10^{-5} \text{ eV}^2 .$$

In a scheme of mass-degenerate neutrinos, the decay:

$$\nu' \rightarrow \nu_e \, \gamma$$

would give rise to a photon of energy $E_\gamma = E_\nu \, \delta m^2 / 2m^2$.

If the individual neutrino masses are around 1 eV, the expected photons fall in the visible range. One can look for them with a telescope. But the sun sends some $10^{17}\gamma/\mathrm{cm}^2/\mathrm{s}$ to Earth, and the idea was to profit from a total solar eclipse which reduces by 8 orders of magnitude the flux of these direct photons. During an eclipse, the neutrinos traverse the Moon and they may decay over the distance between the Moon and the Earth, a 370 000 km decay path.

Taking advantage of the eclipse of 24 October 1996 in Southeast Asia, a telescope pointed to the central core of the sun hidden behind the Moon, where the ^{7}Be neutrinos originate. The measurement lasted 20 seconds with a CCD imaging a quarter of the apparent sun surface. No excess photons were detected in the central part of the CCD where a signal of decaying neutrinos would have been registered. This allowed the limit [13] to be extracted:

$$\tau > 1000 \text{ s} .$$

This limit is not very constraining within the Standard Model, but it applies for the first time to the mysterious ^{7}Be component of the solar neutrino flux.

7. Stimulated Neutrino Conversion

Another unusual experiment was discussed by Gonzáles-Garcia et al.,[14] again in the case of mass-degenerate neutrinos.

The CERN neutrino beam is essentially composed of ν_μ's. A stimulated conversion, changing the nature of the neutrinos, could arise in a superconducting RF cavity which constitutes a bath of 10^{26} photons of well-defined energy. The conversion would result in a component of ν_e and/or ν_τ which could be detected in the CHORUS and NOMAD experiments. The calculation shows that the probability of conversion is

$$\Delta N_\nu/N_\nu = (Q/10^9)(P/100 \text{ W})(m/\text{eV})^3(\text{eV}^2/\delta m^2)^3 .$$

With a LEP cavity and one year of data taking, one could reach a limit on the radiative lifetime of:

$$\tau > 10^{19} \text{ s}$$

for the case of $m = 1$ eV and $\delta m^2 = 10^{-5}\,\text{eV}^2$.

This limit is now 100 times larger than the age of the Universe, although it does not improve the existing limit on the corresponding transition magnetic moment.

A similar idea using the Primakoff effect in the Coulomb field of a nucleus was developed by Domokos et al.[15]

8. Conclusion

In the Standard Model, the radiative decay of neutrinos having a mass in the region of cosmological interest is hopelessly slow. Experimental tests are very limited in the laboratory and the process will remain a theoretical possibility for a long time. Even considering the huge amount of fossil neutrinos present all around us, and assuming a ν_τ with a mass of 30 eV, one expects only one photon of 15 eV energy every $(100\ \mathrm{km})^3$ as the result of all the decays having occurred since the beginning of the Universe (this assumes a mixing of 10^{-4} between the ν_τ and other neutrinos).

Nevertheless, these difficult perspectives should not prevent experimentalists from using their ingenuity and pushing the present limits, hoping to finally reach the realm beyond the Standard Model.

1. G. Bernardi et al., *Phys. Lett.* **B166** (1986) 479;
   Phys. Lett. **B203** (1988) 332.
2. J. Nieves, Puerto Rico Preprint PRE 26311 (1982).
3. P.B. Pal and L. Wolfenstein, *Phys. Rev.* **D25** (1982) 766.
4. J.C. D'Olivo et al., *Phys. Rev. Lett.* **64** (1990) 1088;
   C. Giunti et al., *Phys. Rev.* **D43** (1991) 164.
5. A.A. Gvozdev et al., *Phys. Lett.* **B289** (1992) 103;
   Phys. Lett. **B313** (1993) 161.
6. GALLEX Collaboration, *Phys. Lett.* **B327** (1994) 377;
   SAGE Collaboration, *Phys. Lett.* **B328** (1994) 234;
   Homestake Collaboration, *Nucl. Phys.* **B38** (1995) 47;
   Kamiokande Collaboration, *Nucl. Phys.* **B38** (1995) 55.
7. Kamiokande Collaboration, *Phys. Lett.* **B335** (1994) 237;
   IMB Collaboration, *Phys. Rev.* **D46** (1992) 3720.
8. C. Athanassopoulos et al., *Phys. Rev. Lett.* **75** (1995) 2650.
9. K. Hirata et al., *Phys. Rev. Lett.* **58** (1987) 1490;
   R. Bionta et al., *Phys. Rev. Lett.* **58** (1987) 1494.
10. E.L. Chupp et al., *Phys. Rev.* **D62** (1989) 505;
    E.W. Kolb and M.S. Turner, *Phys. Rev.* **D62** (1989) 509;
    L. Oberauer et al., *Astro. Phys.* **1** (1993) 377.
11. A.H. Jaffe and M.S. Turner, Preprint CITA-95-26.
12. J. Bouchez et al., *Phys. Lett.* **B207** (1988) 217.
13. C. Birnbaum et al., to be published.
14. M.C. Gonzales-Garcia et al., Preprint CERN TH-95/282.
15. G. Domokos et al., Preprint JHU-TIPAC 96001.